7-D ASSESSMENT OF POTENTIAL INFLUENCE OF BRIGHTWATER DISCHARGES ON HARMFUL ALGAL BLOOMS IN PUGET SOUND

FINAL ENVIRONMENTAL IMPACT STATEMENT

Brightwater Regional Wastewater Treatment System

APPENDICES

Final

Appendix 7-D
Assessment of Potential Influence of Brightwater Discharges on Harmful Algal Blooms in Puget Sound

August 2003

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EXECUTIVE SUMMARY

Coastal waters all over the world, including Puget Sound, are receiving increasing amounts of nutrients from municipal and nonpoint sources. At the same time, there has been a global increase in the incidence of harmful algal blooms (HABs). Although there is no relationship that has been scientifically established between treated municipal effluent and harmful algae blooms in Puget Sound, the issue is evaluated in this technical memorandum.

Algal blooms are a natural event in the seasonal succession of the marine environment. Most blooms are not harmful to fish, wildlife or humans and occur on an annual basis, typically lasting a few days or weeks. Only a fraction of all the species of algae that inhabit coastal waters are associated with HABs. A few species produce potent neurotoxins that can be transferred through the food web and thus ultimately affect or even kill organisms at the higher trophic levels. Exposure of humans and wildlife to the toxins is primarily through consumption of contaminated seafood. A few HAB species are not toxic but can kill fish by gill obstruction when present at high densities.

Current knowledge of conditions that lead to the development of harmful algal blooms in Puget Sound is insufficient for predicting when and where blooms will occur. Marine biotoxins have been historically present on the west coast of North America. Paralytic shellfish poisoning (PSP) and amnesic shellfish poisoning (ASP) producers are the major biotoxin sources in this area and both have at times severely impacted the shellfish industry. In Puget Sound, PSP, caused by the dinoflagellate *Alexandrium catenella*, has been spreading southward over the past four decades. Whereas both anthropogenic influence and physical forcing are possibly contributing factors, very little is known about causes and mechanisms that trigger HABs or toxin production in this region.

Puget Sound phytoplankton will have limited exposure, if any, to Brightwater effluent as the effluent will be trapped below 55 m during the majority of the growth season. The phytoplankton are primarily restricted by the presence of sunlight required for plant growth to the surface layers above 10 meters. Based upon the trapping depth of the effluent plume, the quality of the effluent, and oceanographic characteristics of the receiving water, it is not likely that effluent from the Brightwater Treatment System will have an impact on the occurrence of Puget Sound harmful algal blooms

1.0. INTRODUCTION

King County has prepared a Draft Environmental Impact Statement (Draft EIS) and Final Environmental Impact Statement (Final EIS) on the Brightwater Regional Wastewater Treatment System. The Final EIS is intended to provide decision-makers, regulatory agencies and the public with information regarding the probable significant adverse impacts of the Brightwater proposal and identify alternatives and reasonable mitigation measures.

King County Executive Ron Sims has identified a preferred alternative, which is outlined in the Final EIS. This preferred alternative is for public information only, and is not intended in any way to prejudge the County's final decision, which will be made following the issuance of the Final EIS with accompanying technical appendices, comments on the Draft EIS and responses from King County, and additional supporting information. After issuance of the Final EIS, the King County Executive will select final locations for a treatment plant, marine outfall and associated conveyances.

The County Executive authorized the preparation of a set of Technical Reports, in support of the Final EIS. These reports represent a substantial volume of additional investigation on the identified Brightwater alternatives, as appropriate, to identify probable significant adverse environmental impacts as required by the State Environmental Policy Act (SEPA). The collection of pertinent information and evaluation of impacts and mitigation measures on the Brightwater proposal is an ongoing process. The Final EIS incorporates this updated information and additional analysis of the probable significant adverse environmental impacts of the Brightwater alternatives, along with identification of reasonable mitigation measures. Additional evaluation will continue as part of meeting federal, state and local permitting requirements.

Thus, the readers of this Technical Report should take into account the preliminary nature of the data contained herein, as well as the fact that new information relating to Brightwater may become available as the permit process gets underway. It is released at this time as part of King County's commitment to share information with the public as it is being developed.

The purpose of the present document is to present a review of our current knowledge of harmful algal bloom occurrence, globally and in Puget Sound, as a means of evaluating whether exposure of harmful algal species to diluted effluent could increase the probability of harmful algal bloom occurrence in Puget Sound.

2.0. BACKGROUND

Coastal waters all over the world receive large amounts of nutrients from wastewater treatment plants and nonpoint sources (NRC 1993). In moderation, nutrient inputs to estuaries and coastal seas can be considered beneficial: they result in increased production of phytoplankton, which in turn can lead to increased production of fish and shellfish. However, excess nutrients can be damaging, leading to effects such as anoxia and hypoxia from eutrophication, nuisance algal blooms, dieback of seagrasses, and reduced populations of fish and shellfish (NRC 1993).

A three year study by Van Voorhis et al. (2002) examined the sensitivity of the Puget Sound's Central Basin to experimental nutrient additions. The study demonstrated that nutrient addition could result in enhanced primary production at all study sites during the summer, and further concludes that consideration should be given to potential changes in species composition and succession in response to elevated nutrient concentrations.

Potential impacts from future plant operations to marine life or humans exposed to the marine environment have been evaluated in the Phase 3 water quality investigation (Parametrix and Intertox 2002). Hazards from exposure to noxious or toxic algal blooms were not included in that analysis.

3.0. WHAT ARE HARMFUL ALGAL BLOOMS?

Algal blooms are a natural event in the seasonal succession of the marine environment. A bloom refers to the rapid multiplication of a particular phytoplankton species that generates a dense population. Springtime conditions - characterized by increasing daylength, light intensity and temperature, ample nutrients and reduced predator populations - are conducive to algal growth and often result in dense patches dominated by one species. Most blooms are not harmful to fish, wildlife or humans and typically last a few days or weeks (Anderson 1995). Their decline is tied to local nutrient depletion, physical dispersion, grazing, or a natural progression of the life cycle. Dense blooms may appear of different colors, depending on the pigmentation of the particular dominant species (e.g., red tides, brown tides). The term "red tides", however, can be misleading, since non-toxic species can bloom and harmlessly discolor the water; conversely, adverse effects can occur when algal cell concentrations are low and the water is clear (Anderson 1995).

Over the past few decades there has been a global increase in the incidence of nuisance and toxic algal blooms - now generally referred to as harmful algal blooms (HABs) (Anderson 1995, Hallegraeff 1995). Four explanations have been offered for this apparent global increase in HABs: 1) increased scientific awareness and monitoring, 2) increased utilization of coastal waters for aquaculture, 3) stimulation of plankton blooms by cultural eutrophication and/or unusual climatological conditions, and 4) transport of dinoflagellate resting cysts either in ballast water or associated with translocation of shellfish (Hallegraeff 1995).

Only a small fraction of all the species of microscopic and macroscopic algae that inhabit coastal waters are repeatedly associated with toxic or otherwise harmful blooms. A few species produce potent neurotoxins that can be transferred through the food web and thus ultimately affect or even kill organisms at the higher trophic levels, e.g. zooplankton, shellfish, finfish, birds, marine mammals and humans (Hallegraeff 1995). Dissolved algal toxins have recently also been shown to affect larval fish development (Lefebvre et al. 2003). A few harmful species are not toxic but can kill fish by gill obstruction when present at high densities (Hallegraeff 1995).

Exposure of humans to the naturally occurring algal toxins is primarily through consumption of contaminated seafood products. Worldwide, the most significant public health problems caused by harmful algae are Amnesic Shellfish Poisoning (ASP), Ciguatera Fish Poisoning (CFP), Diarrhetic Shellfish Poisoning (DSP), Neurotoxic Shellfish Poisoning (NSP), and Paralytic Shellfish Poisoning (PSP) (Hallegraeff 1995). Each of these syndromes is caused by different species of toxgenic algae (many of them dinoflagellates) which occur in various coastal waters of the U.S. and the world.

PSP and ASP producers are the major biotoxin sources in Western North America (Horner et al. 1997). PSP toxins, referred to as saxitoxins, are produced by species of the dinoflagellate genus *Alexandrium*. During *Alexandrium* blooms the toxins accumulate in a variety of shellfish and other filter-feeding invertebrates. The shellfish do not appear to be affected by the toxin (Determan 2003). PSP toxin then accumulates in marine animals that feed on consumers of toxic phytoplankton, such as zooplankton, bivalve shellfish (oysters, mussels, clams), predatory marine snails, crabs, fish, birds, and marine mammals. Mass mortalities among other shellfish-eating animals, including birds, fur seals, foxes, sea otters and humpback whales have been traced to

PSP (Determan 2003). Saxitoxins ingested with contaminated seafood block the sodium channels of nerve membranes, inhibit neural transmission and may cause death (Determan 2003).

ASP is caused by consumption of shellfish and other filter-feeding invertebrates contaminated with domoic acid. This neurotoxin is produced by species of the diatom genus *Pseudo-nitzschia* and was first detected on the west coast of the U.S. in 1991 (Horner et al. 1997). The toxin is a glutamate antagonist that disrupts normal neurochemical transmission in the brain (Wright and Quilliam 1995).

Monitoring for these biotoxins is carried out routinely in all western U.S. coastal states and in Canada (Determan 2003).

4.0. CONDITIONS LEADING TO BLOOM FORMATION

Phytoplankton have a complex set of requirements for survival, growth and reproduction. Their populations are maintained in check by less than perfect environmental conditions. These limiting factors may be chemical, physical or biological, such as the nutrient content of the surrounding water, the amount of light available for photosynthesis, ambient temperature, or the presence of grazer populations. Alterations in any of these factors may elicit changes in the size and/or composition of a phytoplankton assemblage.

HAB outbreaks are often sporadic and localized and therefore difficult to predict. Although the focus of increased research over the last 10-15 years, basic questions relating to bloom dynamics – conditions leading to bloom formation, persistence, and senescence (i.e., aging) – and biotoxin production remain largely unanswered.

While HABs are largely a natural phenomenon triggered by seasonal changes in seawater temperature, salinity and solar illumination, research has implicated coastal pollution as a major contributor to the global increase in HABs (Smayda 1990, Anderson 1995, Hallegraeff 1995, Horner et al. 1997, Parsons and Dortch 2002). Dissolved organic material has been related to the growth of harmful algal species and initiation of blooms in the inland waterways of the Eastern United States (Hallegraeff 1995). Changed patterns of land use, such as deforestation, can also cause shifts in phytoplankton species composition by increasing the concentrations of humic substances in land run-off, and agricultural run-off has been shown to stimulate algal blooms (Hallegraeff 1995). Conditions leading to HAB outbreaks are likely to involve a combination of factors, including macro- and micronutrients, temperature, and light, as well as precipitation and oceanographic factors. Global climate change (e.g., increases in temperature or UV radiation) further complicates attempts to identify environmental triggers for HABs.

4.1 Macronutrients (N and P)

Many algal bloom species appear to be stimulated by anthropogenic eutrophication from domestic, industrial and agricultural wastes (Hallegraeff 1995). For example, the number of red tides per year in Hong Kong Harbour increased 8-fold in the period 1976 to 1986 (Hallegraeff 1995). This increase was correlated with a 6-fold increase in human population and the concurrent 2.5-fold increase in nutrient loading, mainly untreated domestic and industrial waste. A similar experience was noted in the Seto Inland Sea, a major fish farm area in Japan, as red tide outbreaks increased concurrently with loading of sewage and industrial waste. A study by Parsons and Dortch (2002) provides evidence for a possible link between coastal eutrophication and blooms of Pseudo-nitzschia, and Walsh et al. (2001) cite dissolved organic nitrogen as a primary factor in the development of large blooms of the toxigenic dinoflagellate Gymnodinium breve on the West Florida shelf.

Although nutrient pollution from sewage, fertilizers, and runoff has frequently been flagged as a major contributor to the global increase in harmful algal blooms, there is evidence that the absolute amount of nutrients entering coastal waters may not be as critical as their relative ratios (Hallegraeff 1995, Hodgkiss and Ho 1997). Because large differences exist in the nutrient requirements of different phytoplankton species, shifts in the proportions of key nutrients can result in changes in species composition (Brand 1991).

For example, altered silica:phosphorus (Si:P) ratios from increased phosphate loading in coastal waters may favor blooms of nuisance flagellate species which replace the normal spring and autumn blooms of siliceous diatoms (Hallegraeff 1995). An unusually toxic bloom of *Chrysochromulina* in Norway in 1988 has been related to a change in the nutrient status from nitrogen to phosphorus limitation (Hallegraeff 1995). In a study of Hong Kong red tides, Hodgkiss and Ho (1997) found a correlation between even slight perturbations in the ratio between inorganic nitrogen and phosphates and red tide outbreaks. Some toxic dinoflagellates produce more saxitoxin when phosphorus is deficient (high N:P ratio) (Anderson 1990). The cells become more toxic under phosphorus limitation, probably because cell reproduction is reduced but the cells continue to produce saxitoxin.

4.2 Iron

The theory of iron limitation has effectively explained why large areas of the open ocean which are rich in macronutrients exhibit very low productivity. In contrast, iron limitation has not been thoroughly documented in estuarine environments. Although continental-shelf sediment is expected to provide ample iron to coastal phytoplankton (Johnson et al. 1999) experimental results have shown that phytoplankton can be iron limited in coastal upwelling regions (Hutchins and Bruland 1998). It is also possible that transient iron limitation occurs in many estuarine systems, especially during periods of rapid algal growth. Because large differences exist among marine phytoplankton in their minimum iron requirements, iron availability may influence phytoplankton species composition (Brand 1991). For example, experimental iron addition in the California coastal upwelling region promoted the growth of large chain-forming diatoms (Hutchins and Bruland 1998).

Iron has long been a presumed triggering factor of dinoflagellate red tides in some eastern U.S. coastal areas (Ingle and Martin 1971, Doucette and Harrison 1991). Experimental studies suggest that the iron requirement of some red tide organisms may be greater than that of other phytoplankton and thus more susceptible to iron stress than many other coastal species (Doucette and Harrison 1990, Wells et al. 1991). A study in the Gulf of Maine indicated that while iron input did not trigger outbreaks in coastal waters, pulsed inputs of iron may be important for the development of toxigenic dinoflagellate blooms in regions where outbreaks are initiated offshore (Wells et al. 1991).

A number of studies have investigated the relationship between iron and production of domoic acid by species of Pseudo-nitzschia. Because the carboxylic acid residues of domoic acid can bind trace metals such as iron, it has been hypothesized that release of domoic acid may serve a role in extracellular iron sequestration when cells are iron-limited (Maldonado et al. 2002). Studies with P. multiseries and P. australis clones isolated from Monterey Bay, California, showed that domoic acid release is linked to iron limitation and suggest that domoic acid enhances iron uptake by serving as an extracellular organic chelator (Hutchins et al. 1999, Maldonado et al. 2002). Maldonado et al. (2002) conclude that the ability of these species to augment their iron acquisition could be critical for their success in coastal waters. In a different study with P. multiseries, however, domoic acid production was significantly higher in iron-replete cells than in iron-limited cells (Boyer et al. 2001). In this study, lack of available iron strongly inhibited the ability of the cells to produce domoic acid in culture, presumably due to a metabolic requirement for iron in nitrate reduction and chlorophyll synthesis, processes that provide precursors for the biosynthesis of domoic acid.

Growth of HAB organisms may also be stimulated indirectly by increasing the amount of iron available to the biological community as a whole. For example, it has been shown that dust clouds that are carried by easterly winds from the Sahara Desert across the Atlantic Ocean fertilize the Gulf of Mexico with iron (Lenes et al. 2001). The iron is then used by nitrogen-fixing bacteria, thereby adding biologically usable nitrogen to the water, which in turn was found to stimulate the growth of the toxic red tide alga Karenia brevis.

The relationship between iron and coastal algal blooms remains ambiguous, primarily because the proportion of iron in seawater that is available to phytoplankton is very difficult to quantify (Wells et al. 1991). The bulk of iron occurs in particulate and colloidal forms, which must first dissolve to produce the soluble species assimilated by phytoplankton (Kuma and Matsunaga 1995). Dissolved iron is predominantly bound to organic ligands, but the origin, chemical identity and biological availability of this complexed iron is largely unknown (Hutchins et al. 1999). Moreover, the fraction of iron that is available to phytoplankton is not constant but can differ substantially across small spatial and temporal scales in nature (Wells et al. 1991). It is therefore important to note that the total iron content in seawater cannot be used reliably to determine iron availability or to predict population outbreaks based on iron requirement.

4.3 Sulfur

One of the treatment alternatives for Brightwater employs effluent dechlorination with sodium bisulfite, which could add sulfur to the receiving waters. At present, no evidence exists of a link between ambient sulfur levels and frequency or magnitude of red tides and/or harmful algal blooms (Vera Trainer, John Wekell, and Rita Horner, personal communication to Gabriela Hannach).

4.4 Biological interactions

Phytoplankton blooms can result when predator and phytoplankton populations become uncoupled, i.e., blooms occur when the animal populations are insufficient to consume plant matter at the rate that it is generated (Strickland 1983, Jumars 1993). In some areas of the ocean, tight coupling between the two populations effectively maintains phytoplankton standing stocks at a constant level throughout the year. In Puget Sound, under spring conditions that are conducive to phytoplankton growth, blooms are possible because grazing pressure does not intensify until later in the season, likely initiated by copepod and euphasiid larvae produced from a small population of adult herbivores surviving the winter (Strickland 1983). A general decrease in net primary production past the summer solstice in Puget Sound may also be largely influenced by increased zooplankton populations. Because zooplankters are selective feeders, the phytoplankton community will influence both the amounts and the types of zooplankton present, in turn affecting food availability for higher trophic levels (Strickland 1983).

Whereas grazing and nutrient supply are considered major factors controlling primary production at the community level, these two factors are generally not independent of each other (Jumars 1993). For example, in regions where nutrient supply is not limiting, grazing is more likely to set a limit on phytoplankton biomass. The combination of grazing with nutrient exhaustion is also considered a major driver for bloom collapse (Jumars 1993).

Few studies have addressed the effects of biological interactions on HABs. Some studies have shown that zooplankton avoid or reject certain HAB species (Carlsson et al. 1990). For example, copepods and other macrozooplankton reduce their grazing rates when they encounter dense blooms of some toxic dinoflagellates, and Heterosigma is avoided by some predators (http://www.whoi.edu/redtide/).

Bacterial-phytoplankton interactions are gaining recognition as an important factor in the dynamics of harmful algal blooms. In some cases bacteria may be directly involved in the production of biotoxin by algal cells and some bacteria may even be capable of autonomously producing PSP related biotoxins (Gaudet et al. 2001).

4.5 Hydrographic Factors

Understanding the role of hydrographic and oceanographic factors in bloom initiation and dispersion is making advances as HAB monitoring programs worldwide have generated years of data that can be analyzed in relation to hydrological and meteorological factors. For example, red tides are annually recurrent events in the Gulf of St. Lawrence in northeastern Canada. Analysis of a 10-year data set revealed large yearly fluctuations in the onset, duration and magnitude of the blooms (Weise et al. 2001) that could largely be explained in terms of precipitation, river run-off and wind regime. Yin and Harrison (2001) examined a 15-year dataset for red tides in Hong Kong waters and found that the spatial and temporal patterns appeared related to the seasonal monsoons. As these winds reduce the flushing rate of semi-enclosed waters conditions become more favorable for phytoplankton blooms.

Physical transport has been recognized as an important factor in bloom development (Fauchot et al. 2001), and hydrographic forces may serve to concentrate algal populations. For example, red tide outbreaks on the coast of Hong Kong and Guangdong Province are believed to be caused by cells riding currents from the South China Sea. On the Washington coast, an eddy in the Juan de Fuca region has been identified as a hotspot for toxic Pseudo-nitzschia (Marchetti et al. 2002, Trainer et al. 2002). It has been hypothesized that the area supports a seed population and that cells are propagated along the coast by the eddy.

5.0. HARMFUL ALGAL BLOOMS IN PUGET SOUND

Marine biotoxins have been historically present on the west coast of North America. Pacific coast Native Americans were aware of PSP and believed that shellfish toxicity was related to red tides and bioluminescence (Horner et al. 1997). Very little is presently known about the causes and mechanisms that trigger HABs or toxin production in this region or even the temporal/spatial distribution of the causative species (Taylor and Horner 1994, Postel and Horner 2001, Horner et al. 1997). Puget Sound is a fjord with a deep channel and numerous bays on the western and southern margins. Many of these bays are poorly flushed and experience marked seasonal stratification that favors development of phytoplankton blooms (Horner et al. 1997). Red tides are produced when dinoflagellates are abundant enough to discolor the surface waters. Although these occur throughout the west coast region, none of the truly red tide-forming species on this coast are known to be toxigenic (Horner et al. 1997). Harmful algal blooms in Puget Sound are likely not linked to those along the open coast, but instead originate in situ (Horner et al. 1990, 1997).

Most of the existing data on HABs for the west coast focus on commercial and recreational shellfish harvesting and is thus based on detection of toxin in shellfish rather than on monitoring phytoplankton species composition and abundance (Horner et al. 1997). Postel and Horner (2001) have been monitoring selected sites on the Washington outer coast and on Puget Sound inland waters since 1990. Their bi-monthly sampling from 1997 to 2000 indicated that potentially harmful species were present at one or more sites in all months (except March 1999) and that harmful genera occurred at all sites.

Harmful algal species on this coast are presumably native to the area (Table 1). The two genera responsible for recurrent toxic blooms on the west coast are the diatom Pseudo-nitzschia and the dinoflagellate Alexandrium (Horner et al. 1997). These organisms can produce natural biotoxins that accumulate in shellfish, finfish and marine mammals and thus present a health risk for humans and marine mammals. The Washington State Department of Health Biotoxin Program performs year-round monitoring of PSP and ASP in molluscan shellfish from both recreational and commercial harvest areas (http://www.doh.wa.gov/ehp/sf/BiotoxinProgram.htm) and lists beaches that are closed to recreational harvest in their Biotoxin Bulletin (http://ww4.doh.wa.gov/gis/biotoxin.htm). Catastrophic losses of cultured and wild fish also have occurred due to two algal genera that do not cause illnesses in humans, Chaetoceros and Heterosigma (Horner et al. 1997). Other potentially harmful species exist in Puget Sound, notably Dinophysis spp. (Postel and Horner 2001, Horner et al. 1997), but since toxic outbreaks of these species have not been reported for the west coast, they will not be discussed further.

Table 1. Potentially Harmful Algal Species Identified in Puget Sound Waters and Local Organisms Directly or Indirectly Affected.

Species	Algal group	Harmful Effect	Affected Organisms
Alexandrium catenella	Dinoflagellate	Saxitoxins cause Paralytic Shellfish Poisoning (PSP)	Accumulates in bivalve shellfish (mussels, clams, oysters). Harmful to shellfish consumers.
Pseudo-nitzschia spp.	Pennate diatom	Domoic acid causes amnesic shellfish poisoning (ASP)	None reported in Puget Sound (1).
Chaetoceros spp.	Centric diatom	Non-toxic. Fish kills by gill obstruction.	Pen-reared finfish
Heterosigma akashiwo	Raphidophyte (brown flagellate)	Mechanism unknown. Fish kills.	Wild and pen-reared salmon

(1) On the outer Washington coast, domoic acid poisoning affects primarily consumers of razor clams and Dungeness crabs.

The four species listed in Table 1 are discussed further below.

5.1 *Alexandrium*

Species of the dinoflagellate genus *Alexandrium* produce a group of neurotoxins known as saxitoxins that accumulate in filter-feeding shellfish and other invertebrates (Determan 2003). Consumption of shellfish that contain high levels of toxins can result in potentially lethal paralytic shellfish poisoning (PSP). Toxicity from *Alexandrium* blooms - commonly known as a red tide - is a serious problem worldwide (Hallegraeff 1995).

In Washington PSP is caused primarily by *A. catenella*, a chain-forming species that ranges from Alaska to California, but other *Alexandrium* species may also be involved (Horner et al. 1997, Trainer et al. in press). The toxins are concentrated by bivalve shellfish (oysters, mussels and clams) yet the shellfish do not appear to be affected by the toxin (Determan 2003). PSP in shellfish has been monitored throughout Washington State since the late 1950s (PSWQAT 2002), when it was determined that shellfish toxicity is an annual phenomenon on the outer coast and annual recreational shellfish closures were established. The Washington State Department of Health (DOH) presently maintains two biotoxin monitoring programs (Determan 2003). In Puget Sound, one program monitors biotoxin in numerous species of clams and oysters at hundreds of locations throughout the sound. Another program monitors levels of PSP toxin in mussels – which bioaccumulate the toxins at a faster rate than other shellfish - taken every two weeks at a smaller number of sentinel sites (Determan 2003).

PSP was initially uncommon in the inner protected waters of Puget Sound (the first closure occurred in 1971) but outbreaks have since increased. Toxicity has spread southward from the Whidbey Basin and now only parts of the Hood Canal and Totten Inlet in south Puget Sound remain PSP-free (Determan 2003, Trainer et al. in press). Results from 30 sites monitored by DOH in Puget Sound are examined annually to determine spatial patterns and temporal trends as part of the Puget Sound Ambient Monitoring Program (Determan 2003). DOH data from 2000 indicate greatest PSP impact at scattered sites in the Main Basin and south Puget Sound (PSQWAT 2002).

Trainer et al. (in press) examined the general trend for PSP in Puget Sound using 45 years of data collected by DOH. Their analysis indicated that there has been a southward spread of toxigenic algae over the past four decades along with an approximately tenfold increase in maximal levels of paralytic shellfish toxins (Figure 1). Both anthropogenic influence and physical forcing are cited as probable contributing factors. Based on both monitoring and experimental data, Rensel (1993a) has suggested that the low concentration of surface and subsurface nitrogen in the unaffected areas of southern Puget Sound has prevented further spread of *A. catenella* to these areas.

When not in bloom, cells of *Alexandrium* are only found sporadically in Puget Sound and are often absent from phytoplankton monitoring samples (Postel and Horner 2001). Cysts of *Alexandrium* are resistant to environmental extremes and may provide seed populations for future blooms (Horner 1996). The complicated interaction of factors leading to bloom development is still poorly understood. Ecological studies of *A. catenella* bloom dynamics in Puget Sound suggest that blooms originate *in situ*, and that conditions favoring bloom growth include development of a warm (14 oC) surface layer, increased nutrient loading, and reduced turbulence (Horner et al. 1997). Postel et al. (2001) examined the factors leading to *A. catenella* bloom decline. Their research on the dynamics of blooms in Quartermaster Harbor - a small, semi-enclosed, seasonally stratified bay on Vashon Island - indicated that decline is brought about by a combination of biological (e.g. grazing), chemical, and physical (e.g. tidal mixing) factors. Ebbesmeyer et al. (1995) compared the decadal variation of PSP in Sequim Bay with selected environmental factors. Their results suggest that PSP toxicity increases during warm and dry years, whereas PSP toxicity decreases during cold and wet years.

5.2 *Pseudo-nitzschia*

Domoic acid is produced by several species of the genus *Pseudo-nitzschia*, a planktonic pennate diatom (Horner et al. 1997). In Washington, domoic acid occurs mostly on the outer coast and to date has only affected razor clams and Dungeness crabs (R. Horner pers. comm.). The toxin is passed along the food chain, resulting in amnesic shellfish poisoning (ASP) – also called domoic acid poisoning (DAP) - of humans, sea birds and marine mammals.

Domoic acid is a problem for both commercial and recreational fishing on the outer Washington coast but has not caused shellfish closures in inland Puget Sound waters to date (Horner et al. 1997). Causative species may include *P. pseudodelicatissima*, *P. australis*, *P. pungens*, and *P. multiseries*. Also present on the coast are *P. fraudulenta*, *P. heimii* (uncertain identification) and P. delicatissima (R. Horner pers. comm.). While all of these species have been identified when domoic acid was present, it is not known whether all of them can produce the toxin. Offshore initiation sites have been characterized for toxic *Pseudo-nitzschia* blooms. These are areas where cells are concentrated in water masses associated with offshore eddies or in upwelling zones near coastal promontories (Trainer et al. 2002, Evans et al. 2003). Initiation sites may provide the seed for blooms spreading along the coast. A difficulty in tracking *Pseudo-nitzschia* is that it is generally not the dominant organism in an algal bloom (N. Evans pers. comm).

Whereas *Pseudo-nitzschia* are common on the Washington open coast and also at various monitoring sites in Puget Sound and Hood Canal, high cell concentrations occur only rarely in the inland waters and to date have not caused any toxic events (Albertson et al. 1995, Horner et al. 1997). All of the outer coast species (with the possible exception of *P. heimii*) are also present in Puget Sound (R. Horner, pers. comm.). In the sound, domoic acid has been found only in small concentrations, not enough to cause shellfish harvest closures. For example, during the summer of 1997 a large bloom of *Pseudo-nitzschia* in Penn Cove, a small bay on Whidbey Island, persisted for about two months with no evidence of toxigenicity (NWFSC online).

5.3 *Heterosigma*

H. akashiwo is a small, brown flagellate alga that has been responsible for major fish kills in temperate regions worldwide (Taylor 1990, Honjo 1993). The toxicological mechanism involved in the fish kills is still unknown, although some evidence points to production of superoxide and hydroxyl radicals and hydrogen peroxide (Horner et al. 1997). Symptoms in fish include loss of equilibrium, gill damage, and respiratory paralysis (Red Tides 1999). Mechanisms of toxicity induction in *H. akashiwo* blooms also remain unclear. Highly lethal and relatively benign blooms can occur in the same geographic area, suggesting that conditions that enhance toxicity are possibly very different from those conducive to bloom formation (Connell and Jacobs 1999). A study on the role of nutrients in toxic blooms of *H. akashiwo* in the Strait of Georgia suggests that there exists a link between toxicity and the timing and quantities of nutrients (Black 2002).

The species has been in Pacific Northwest waters for at least 30 years, but was not known to produce deadly blooms until the 1980's. Postel and Horner (2001) reported that *H. akashiwo* cells are rarely present in their bimonthly monitoring samples from Puget Sound and the outer Washington coast. Nonetheless, blooms have caused significant losses of both cultivated and wild salmon in Puget Sound (Red Tides 1999).

Blooms often start in shallow back bays of Puget Sound and spread into the sound, carried by tides and currents (Horner et al. 1997). *H. akashiwo* is a vertical migrator, usually occurring in surface waters during the day and at depth during the night (Boesch et al. 1997). Vertical stability of the water column is probably an important factor in maintaining blooms. In September of 2000 a bloom of *H. akashiwo* was first recorded in southern Hood Canal, with cell numbers reaching 2.7 x 108 cells/l (Connell et al. 2001). This bloom did not have any apparent adverse effects on fish.

5.4 *Chaetoceros*

This genus has been implicated in extensive fish kills caused by gill clogging and obstruction (Rensel 1993b). The causative mechanism has not been conclusively demonstrated, but no toxin is involved. *C. convolutus* and *C. concavicornis* are two morphologically similar species implicated in kills of pen-reared salmon in the Pacific Northwest. A third species, *C. danicus*, may also be associated with Puget Sound fish-kills (Horner et al. 1997). These chain-forming diatoms are armed with long, barbed, siliceous setae (spines) that break off and clog the gills of salmon. Gill tissue becomes irritated and produces copious mucous, and the salmon eventually die from suffocation or secondary infection (Horner et al. 1997).

It is known that *Chaetoceros* blooms can cause fish kills at low cell densities, and that depending on local hydrographic conditions, the cells may be restricted to near-surface waters or mixed throughout the water column (Boesch et al. 1997). To date, very little is known about how environmental parameters influence the magnitude and the timing of *Chaetoceros* blooms in Puget Sound (Horner et al. 1997).

6.0. PROPOSED BRIGHTWATER TREATMENT PLANT

Secondary treated effluent from the proposed Brightwater Treatment Plant will be discharged at one of two potential offshore locations: The Route 9 alternative for the treatment plant (preferred by the Executive) would have a marine outfall located offshore of Point Wells. The Unocal treatment plant marine outfall would be located offshore of Edwards Point in Edmonds. At either location, the outfall will be at least 500 feet (150 m) deep and 3,000 feet from shore.

Effluent will be discharged through a diffuser to enhance mixing of the freshwater effluent with the marine receiving waters (Figure 2). After discharge, movement and mixing of effluent with marine water are controlled primarily by differences in density between effluent and the surrounding water. These differences cause the effluent to mix with the marine water and when it reaches ambient density through mixing, it stops rising at the trapping depth. The diluted effluent is subsequently dispersed primarily by ocean currents; over the long-term it will approach a steady-state concentration equilibrium. The Basin Scale model conservatively predicts that steady-state dilutions will range from 2220:1 to 4440:1 in the upper 50 m of the Main Basin (Parametrix and Intertox 2002). This means that throughout this upper layer constituent concentrations are expected to level out at 0.023% - 0.045% of their initial concentration in the effluent.

Membrane bioreactor (MBR) technology has been selected as the preferred alternative for Brightwater's secondary treatment process (Parametrix 2003). MBR combines an activated sludge process and solid separation by low pressure membrane filtration (nominal pore sizes of 0.1-0.4 mm), yielding an effluent that is highly clarified and low in ammonia when compared to conventional secondary treatment systems, and is expected to remove 72-85% of the total ammonia (Parametrix 2003). In addition, N:P and ammonia:nitrate ratios in the MBR effluent more closely match the receiving waters than conventionally treated effluent (Parametrix 2003, Sukapanpotharam and Bucher 2003).

The MBR process is a split flow process due to the limited peaking capacity of the membrane system. During certain times of the year when high flows occur, flows above the designed threshold would be split downstream of preliminary treatment and treated by ballasted sedimentation, an advanced primary treatment system. The ballasted clarifier uses iron oxide pellets in a sedimentation tank. Most of the added iron (70 mg/l ferric chloride) is expected to remain in the tank (data on iron retention not yet available). The split flows would be recombined for discharge to Puget Sound via a deep-water marine outfall.

Effluents would be disinfected prior to recombination at the Unocal site and after recombination at the Route 9 site. Addition of sodium hypochlorite at 2.0 mg/l may be followed by dechlorination with sodium bisulfite at 1.0 mg/l if required (King County 2003), but this system would be used infrequently. For the Route 9 site, it is anticipated that the long travel time from the treatment plant to the outfall will consume any chlorine residual that would require dechlorination prior to discharge into Puget Sound. For effluent from the Unocal site, ultraviolet light would be used for the MBR effluent (no sodium bisulfite would be required) and sodium hypochlorite followed by dechlorination with sodium bisulfite would be used for the effluent from the ballasted sedimentation process. The latter would only be used a few times a year during high flows in the winter.

7.0. POTENTIAL FOR IMPACTS

7.1 Where are the phytoplankton?

Phytoplankton may be present throughout the euphotic zone, generally defined as the layer of water that receives ≥1% of the light incident on the sea surface. Within this zone, vertical distribution is uneven and is usually characterized by a clearly defined subsurface maximum. Many dinoflagellate species, including *A. catenella*, exhibit vertical migration, spending the day close to the surface to photosynthesize and migrating down to nutrient richer water during the night (Horner et al. 1997). Some species may have non-motile resting stages that sink to the bottom and may remain there for extended periods of time.

The depth of the euphotic zone varies with the seasonal fluctuations in the amounts of suspended particles that limit light penetration (e.g. live cells, detritus, sediment from runoff): it is typically shallowest in late spring and late summer coinciding with times of high algal productivity and deepest in the fall as production ceases and dead cells settle out. Suspended sediment particles from runoff may limit light penetration considerably during the rainy season. Vertical profiles carried out throughout the year between 1998 and 2001 at 4 Puget Sound sampling stations (Admiral Inlet, Point Wells, Possession Sound and West Point) yielded euphotic zone depths ranging from 7 to 45.5 m (Van Voorhis et al. 2002). At Point Wells, the station closest to the proposed outfall locations, the depth of the euphotic zone varied between 9.1 and 42.1 m (mode = 22.1 m, Figure 3).

7.2 Will phytoplankton be exposed to effluent?

The EPA PLUMES Version 3 model (EPA 1994) was used by West Consultants and Parametrix (2002) to predict the submergence of a plume when it reaches its trapping level. Four model parameters define submergence or depth of the trapping layer: diffuser length, discharge rate, current speed, and water column stratification. The modeling predicts that during late spring and summer, when density stratification is most pronounced and phytoplankton production is high, the trapping layer will remain at depths greater than 55 m (Table 10 in West Consultants and Parametrix 2002), clearly exceeding the depth of the euphotic zone. This implies that during the growth season phytoplankton exposure to effluent will be limited to the steady-state concentrations that will be present in the bulk of the Main Basin. During times of the year when the water column is not stratified the trapping layer will rise and may approach the sea surface. Under these conditions the mixing layer may penetrate the euphotic zone. However, because an unstratified water column typically only occurs during the winter when phytoplankton production is negligible, the effluent present in the mixing layer should not affect phytoplankton production during this time. Exceptions could occur during early spring, when algal populations are experiencing a growth burst and density stratification is still in development.

8.0. SUMMARY AND CONCLUSIONS

Effluent plume modeling predicts that, during the summer when density stratification is most pronounced and phytoplankton production is high, the Brightwater effluent plume will remain trapped at depths greater than 55 m, exceeding the depth of the euphotic zone. During most of the growth season, phytoplankton would therefore be exposed to highly diluted effluent, if at all.

Membrane bioreactor (MBR) technology yields an effluent that is highly clarified, low in ammonia, and with N:P and ammonia:nitrate ratios that more closely match the receiving waters when compared with conventionally treated effluent (Parametrix 2003). Maintaining a natural balance in nutrient ratios is an important consideration, given that these ratios have been shown to play an important role in algal growth and other physiological processes and, specifically, that changes in these ratios have been implicated as triggers for HABs (Hodgkiss and Ho 1997).

The MBR system will use a ballasted primary clarifier containing iron oxide when the membrane exceeds its average wet weather capacity (King County 2003). The majority of the added iron is expected to remain in the tank. While iron is generally not a limiting nutrient in coastal areas (Johnson et al. 1999), iron depletion may occur during blooms and this may be a factor that contributes to the natural decline of a bloom. Because iron is required for the uptake and reduction of nitrate (Price et al. 1991), an effluent that is low in ammonia – a reduced source of nitrogen – ensures that the algae remain dependent on the availability of iron for their nitrogen acquisition needs. It is known – at least for one species of *Pseudo-nitzschia* - that lack of available iron may inhibit the ability of the cells to produce domoic acid in culture (Maldonado et al. 2002). It is not known whether iron limitation plays a role in suppressing production of domoic acid by Puget Sound populations of *Pseudo-nitzschia*.

The Brightwater system may use chlorination followed by sodium bisulfite as a means of disinfection. This process would be used infrequently. At present, no evidence exists of a link between ambient sulfur levels and frequency or magnitude of red tides and/or harmful algal blooms (Vera Trainer, John Wekell, and Rita Horner, personal communication to Gabriela Hannach), thus addition of sulfur to the Sound from the dechlorination process is not presently a concern. In addition to the above factors, there have been no scientific studies directly linking treated wastewater effluent to the occurrence of harmful algal blooms in Puget Sound.

Although current knowledge of conditions that lead to the development of harmful algal blooms in Puget Sound is insufficient for predicting when and where blooms will occur, it is not likely that effluent from the Brightwater Treatment System will affect the occurrence of harmful algal blooms. This conclusion is based upon the trapping depth of the effluent plume, anticipated effluent quality, and oceanographic characteristics of the receiving water. Phytoplankton will have limited exposure, if any, to the effluent since the plume will be trapped below 55 m during the majority of the growth season. At times when the effluent may rise to the euphotic zone when water column stratification is weak, a stimulatory effect from nutrients and iron is not likely. This is due to the ammonia removal efficiency and iron retention of the MBR technology as well as rapid dilution at the outfall diffuser. In addition, the outfall will be located in an open area in the Puget Sound Main Basin that is not prone to eutrophication, due to favorable tidal mixing conditions. Eutrophication in Puget Sound has been observed mainly in enclosed embayments with less than favorable tidal mixing.

9.0. REFERENCES

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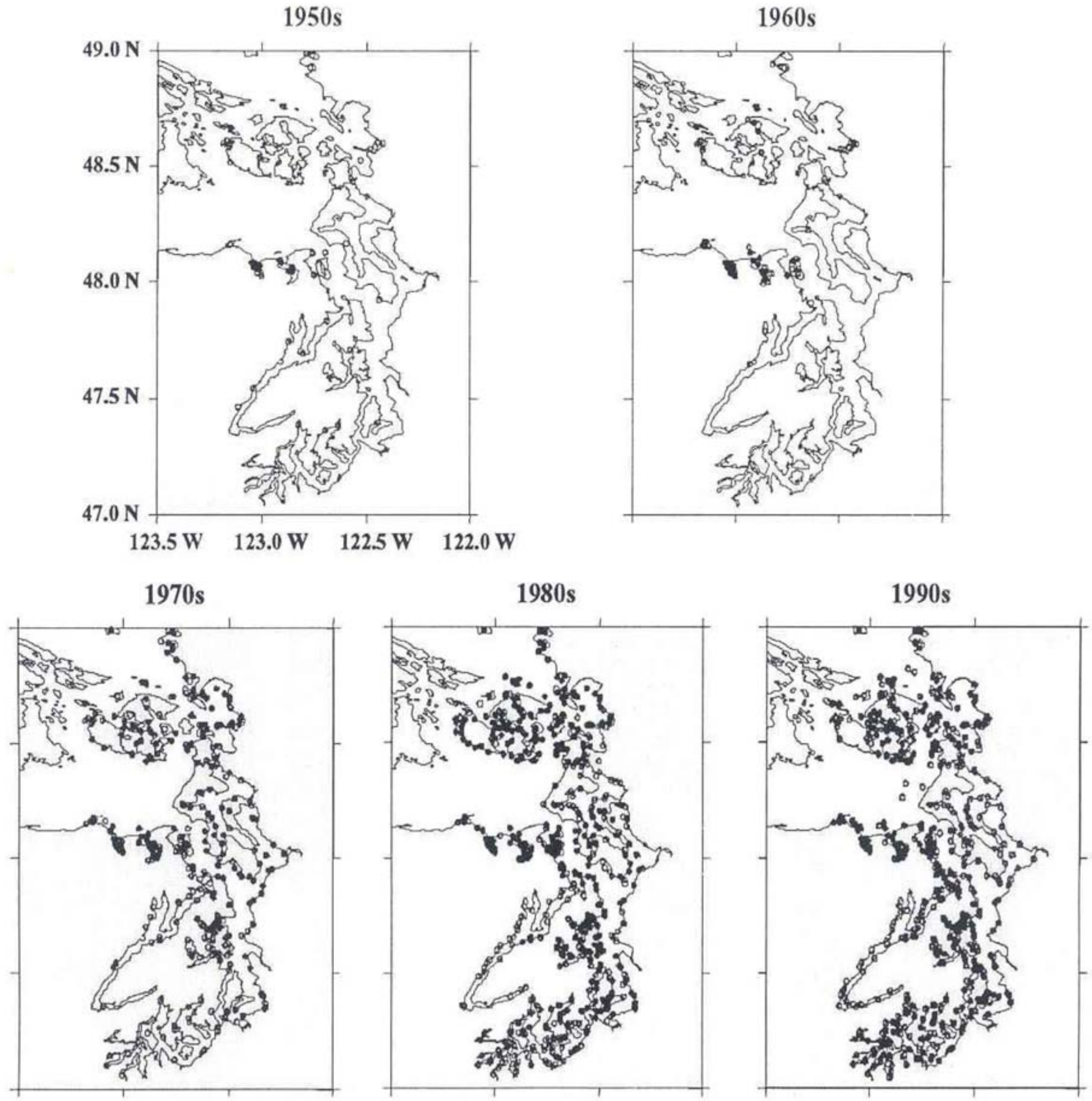
10.0. FIGURES



Shellfish harvesting closure zones due to PSP toxins at all Puget Sound DOH monitoring sites for each decade. Symbols represent maximum values below 80µg/100g (open circles) and at or above 80µg/100g (solid circles. Data for the 1950s includes only 1957-1959 (from Trainer et al. 2003, with permission from J. Shellfish Res.)

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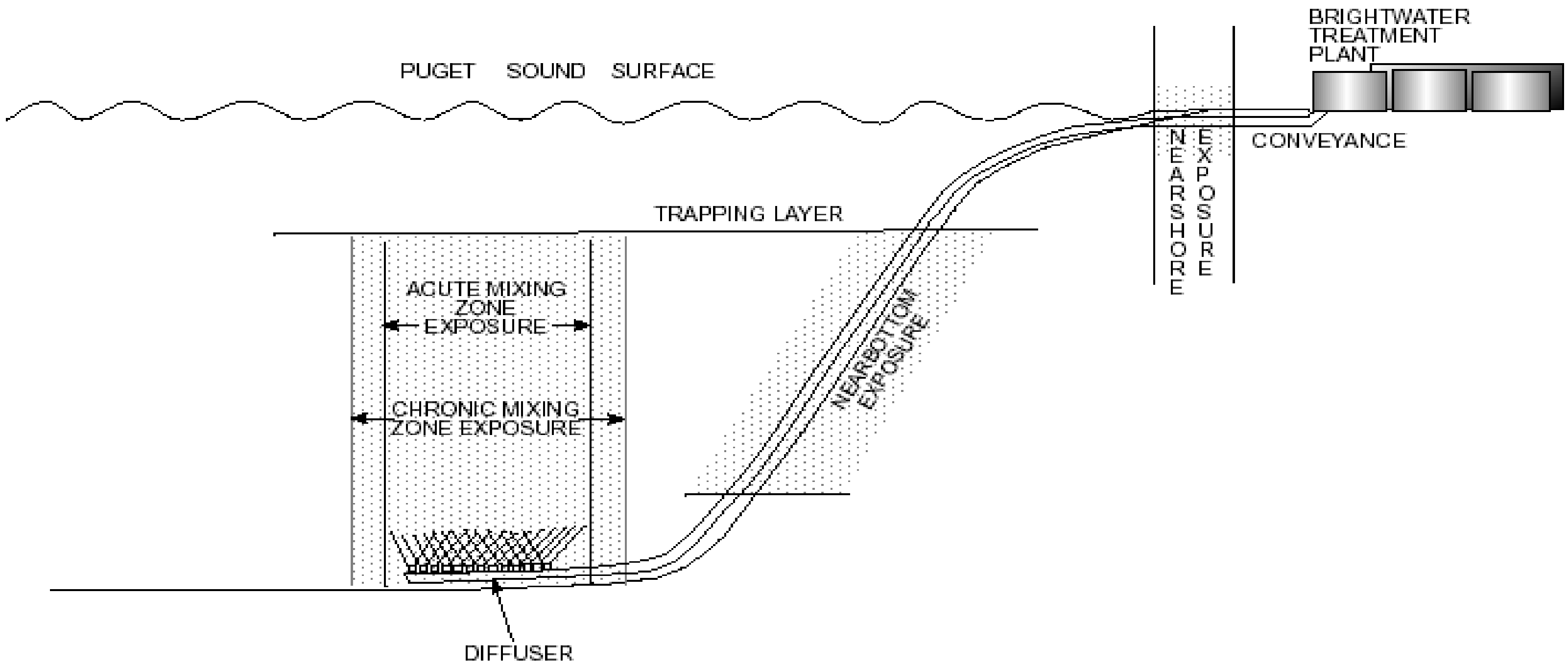
Wastewater Treatment Division

File Name: TM09XF0X
Prepared by: Bruce Nairn

Figure 1

Shellfish Harvesting Closures

BRIGHTWATER REGIONAL WASTEWATER TREATMENT SYSTEM



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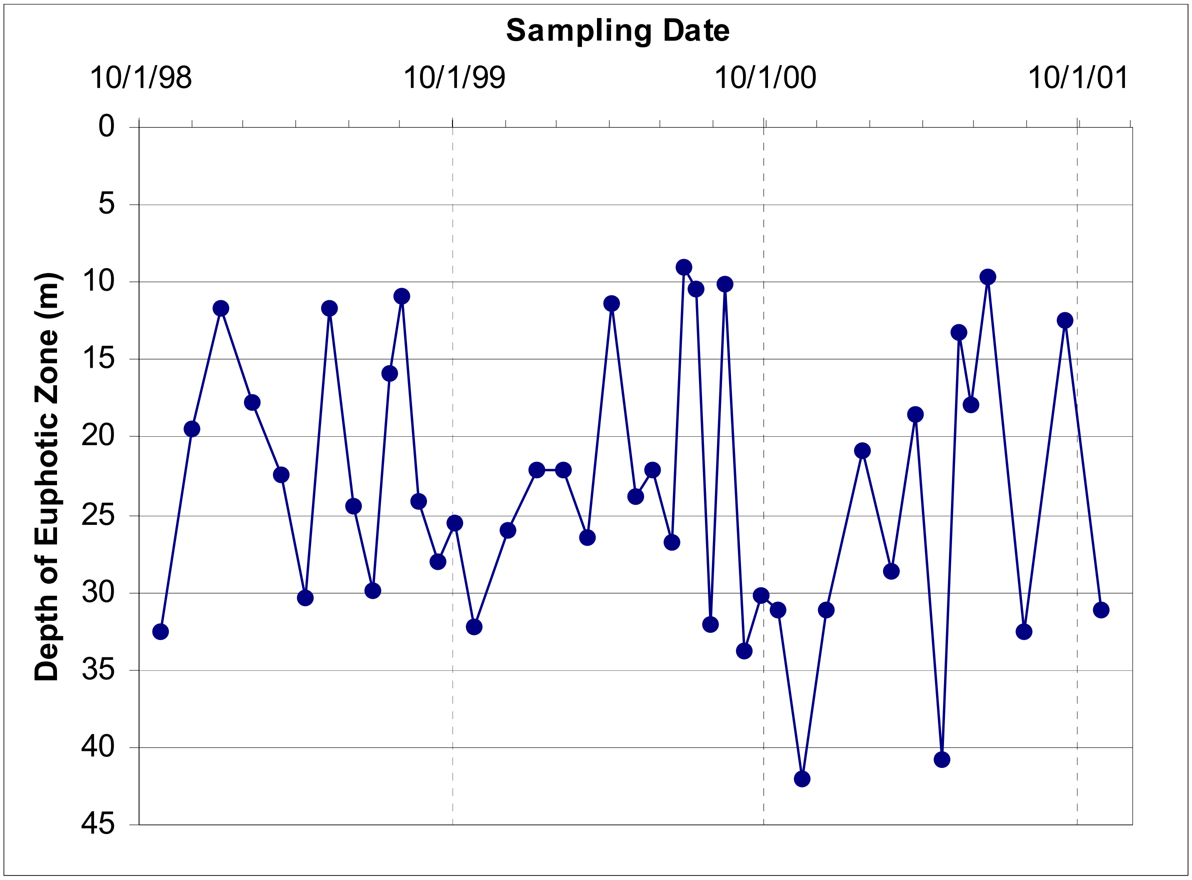
File Name: TM09XF0X
Prepared by: Bruce Nairn

Figure 2

Candidate Outfall Zones Schematic of Exposure Senarios

BRIGHTWATER REGIONAL
WASTEWATER TREATMENT SYSTEM

From data in Van Voorhis et al. 2002.



From data in Van Voorhis et al. 2002.

Figure 3

Depth of Euphotic Zone at Point Wells, 1998-2001.

BRIGHTWATER REGIONAL WASTEWATER TREATMENT SYSTEM